Thirty-Year Durability of a 20-Mil PVC Geomembrane

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In 1971, twenty circular aquaculture ponds were constructed for the W. K. Kellogg Biological Research Station in Hickory Corners, Michigan. The 30.5-m-diameter research ponds were lined using a 0.51-mm-thick fish-grade PVC geomembrane. Over the years the ponds became congested with dense, persistent stands of cattails, trees, and other vegetation, which required the ponds to be cleared and relined in September 2000 in order to allow the initiation of new experiments. The lack of holes in the exhumed geomembrane suggests that it resisted biological attack from microorganisms and also root penetration. Laboratory testing shows that the tensile behavior of the nearly 30-year-old PVC geomembrane is within current specifications for new 0.51-mm-thick PVC geomembranes. Test results also indicate that performing laboratory tests at *in-situ* moisture conditions provides a better estimate of the field properties of PVC geomembranes than desiccating the material prior to testing, as is required by ASTM Standard Test Methods. J. Vinyl Addit. Technol. 10:168–173, 2004.

INTRODUCTION

In 1971, twenty circular aquaculture ponds were constructed for the W. K. Kellogg Biological Research Station at the Michigan State University Facility in Hickory Corners, Michigan, under a grant from the National Science Foundation. Eighteen of the ponds were for experimental purposes and two were for water-storage purposes. The ponds were allowed to colonize naturally with flora and fauna from surrounding lakes, and within a few years the experimental ponds closely resembled natural systems. These conditions provided the opportunity to conduct a number of significant experiments on species interaction and habitat selection in fishes.

The 30.5-m-diameter research ponds were lined using a 0.51-mm-thick fish-grade PVC geomembrane. A fish-grade PVC geomembrane is specially formulated to promote aquatic life by not including biocides used in typical PVC geomembrane formulations. The biocides are excluded because they may leach out over time and injure the fish. The basic formulation of a PVC geomembrane corresponds to 60%−65% PVC resin; 32%−38% plasticizer; 5%−8% stabilizers, additives, and biocides; and 0.5%−1% pigment (1). The ponds are 8 feet deep with side slopes of three horizontal to one vertical. After installation, each PVC geomembrane was covered with 1 foot (0.30 m) of sandy soil cover.

Over time the ponds became congested with dense, persistent stands of cattails, trees, and other vegetation. These conditions made many types of experiments impossible, and thus, to start new aquaculture experiments, nine of the ponds were cleared and relined in September 2000. It is important to note that none of the ponds was leaking or exhibiting any problems during the nearly 30 years of service. However, the initiation of new experiments provided a unique opportunity to exhume approximately 30-year-old (29 years and 8

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DOI: 10.1002/vnl.20025

months) PVC geomembranes and evaluate their engineering properties. Previous researchers have examined PVC geomembranes ranging in age from 2 to 30 years used both as canal liners in the western U. S. (2, 3) and as part of landfill cover systems in Florida (4, 5) and discovered that the geomembranes performed well. This case history is unique because it involves a 0.51-mm-thick PVC geomembrane in an aquaculture environment after nearly 30 years.

On September 13, 2000, Erik Newman of the University of Illinois at Urbana-Champaign (UIUC) removed samples of the geomembrane from the ponds. The samples were exhumed from three locations: 1) the side slopes above the waterline, 2) the side slopes below the waterline and under the cattails, and 3) the bottom of the ponds. The samples were sealed in large plastic bags to minimize moisture loss prior to testing at the UIUC. Some of the samples were shipped to TRI/Environmental in Austin, Texas, for comparison testing.

OBSERVATIONS OF GEOMEMBRANE DURING EXCAVATION

All the samples removed from the pond were soft and flexible, which is evident from their elongation-at-break values, presented subsequently, which still satisfy current specification values. The flexibility of the nearly 30-year-old material also is illustrated in *Fig. 1* by photographs of a tensile specimen from the side-slope material from below the waterline before and during tensile testing. It can be seen that the specimen is undergoing substantial elongation during testing without rupture. Material removed from the bottom of the pond was even softer and more flexible than the material from above the waterline, probably because of less desiccation occurring below the waterline. Once the samples were desiccated in accordance with ASTM test procedures, the samples were somewhat less flexible, which strongly suggests that exhumed material should be tested using *in-situ* conditions, i.e., without desiccation as required by ASTM Standard Test Methods, to properly assess the *in-situ* engineering properties. Desiccated specimens can be used for new material, but it is not recommended for exhumed material because the geomembrane has already become acclimated to field conditions.

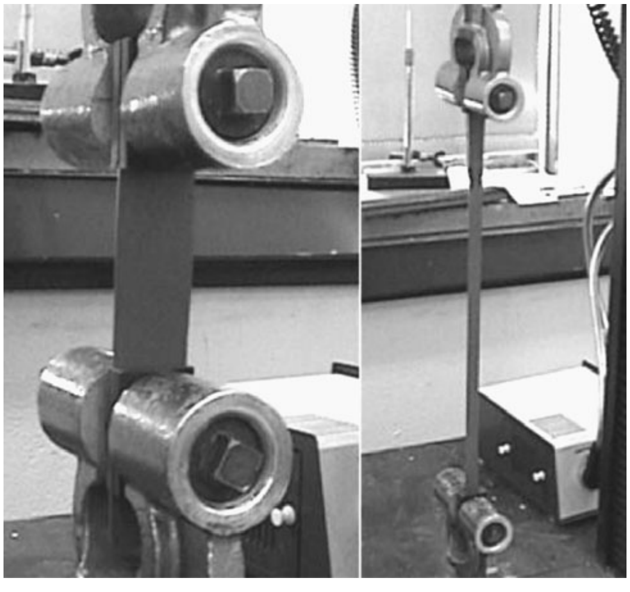

Fig. 1. Exhumed PVC geomembrane before and during tensile testing.

At the center of each pond an inlet/outlet structure was constructed. This structure consisted of a concrete slab, approximately 0.75 m × 0.75 m, with the top level with the liner subgrade. The liner was placed over the concrete, sealed with butyl mastic, and fastened to the concrete using 38 mm × 95 mm redwood batten strips and concrete nails. This structure and the batten performed well over the nearly 30 years, as indicated by no discoloration of the soil under the PVC geomembrane around the structure. These observations also indicate that there was little, if any, leakage through the liner in the vicinity of the inlet/outlet structure. The mastic was soft and flexible after nearly 30 years, which resulted in an effective seal around the nails used to fasten down the strips.

One of the main objectives of this study was to determine the effect, if any, of root penetration and microorganisms on 0.51-mm PVC geomembranes. The ponds were overgrown with vegetation and had a large number of cattails growing around the perimeter and in the middle of the ponds. As the bulldozer removed soil from the top of the geomembrane under the cattail area, observations were made of the root zone of the cattails. These cattails produced one root stalk about 20 to 30 mm in diameter, with a mass of smaller roots around the main root. The root length was approximately 0.3 m to 1 m. All roots of the cattails grew down to the geomembrane and then grew horizontally along the top surface of the geomembrane. No evidence of roots penetrating the 0.51-mm-thick geomembranes was found during field inspection or after holding the exhumed geomembrane over a light source in the laboratory.

In one of the ponds, a small willow tree was growing about 5 feet down-slope of the anchor trench but above the water level. The willow was approximately 4 m tall; its trunk was 150 to 200 mm in diameter. As the bulldozer operator cleared the soil from the sides of the tree, it was observed that the large tree roots also grew down to the geomembrane, then turned and traveled along the surface of the geomembrane. The main tree roots were 1 to 1.5 m long, with some smaller roots extending up to 2 m from the tree trunk. When the dozer pushed the tree over, it slid down the geomembrane to the bottom of the pond, leaving the geomembrane intact. Again no evidence of root penetration was found during field inspection and after holding the exhumed geomembrane from the vicinity of the willow tree over a light source. These observations are especially significant because the geomembrane is only 0.51 mm thick. The reasons the cattails and tree roots did not penetrate the geomembrane include the resistance of the geomembrane to penetration and the fact that the roots grew laterally to remain in the soil. In either case, the adverse anecdotes that PVC geomembranes are penetrated by roots are not supported by this case history.

The lack of observed holes in the geomembrane also suggests that it resisted biological attack from microorganisms. There was no surficial damage to the geomembrane to indicate microorganism attack. This is particularly significant because the experiments introduced many types of microorganisms to the ponds. This qualitative data suggests that there has been no detrimental effect on the geomembrane from root penetration or microorganisms in this harsh and demanding environment since 1971. This case history also rebuts the adverse anecdotes that holes are eaten in PVC geomembranes by microorganisms.

TESTS ON EXHUMED GEOMEMBRANE

Experimental Procedure

Samples of the PVC geomembrane exhumed from above and below the waterline were tested at the UIUC to evaluate the effect of submergence on the engineering properties of the exhumed geomembrane. Only samples exhumed from below the waterline were tested at TRI/Environmental. Samples from each location were tested in both the machine (MD) and transverse (TD) directions. The test results were compared to the National Sanitation Foundation Specification (6), NSF-54, to quantify the changes in material and seam properties of the PVC geomembranes over the 29 years and 8 months of service. The NSF-54 specification was the applicable standard in 1971 when the ponds were constructed and was used for comparison purposes because pieces of the original material were unavailable for testing. To fill the void left by the obsolescence of NSF-54, which was last updated in 1993, the PVC Geomembrane Institute (PGI) developed and has periodically updated a specification for PVC geomembranes. Thus, to further evaluate the performance of the exhumed geomembrane, the corresponding values of the latest PGI specification, PGI-1103 (7), are also shown for each test. The PGI-1103 specification became effective January 1, 2003.

Some of the samples from each location were cleaned and allowed to acclimate and desiccate in the laboratory for 40 hr according to the applicable ASTM standard test methods. Other samples from each location were tested without allowing desiccation in the lab by storing the material in a moist room until testing. This non-desiccation procedure was implemented to provide a better estimate of the *in-situ* properties as the geomembrane was kept at a high moisture content. It is believed that the non-desiccated material provides a better simulation of the field moisture conditions. The desiccated test results presented herein present a worst-case scenario for the engineering properties of the *in-situ* material because the material has been desiccated. The applicable ASTM testing specifications are listed in *Table 1*.

Results and Discussion

The test results shown in *Table 2* are for material obtained from near the bottom of one of the ponds and desiccated prior to testing. *Table 2* shows agreement between the test results obtained from the UIUC and TRI/Environmental (TRI). More important, the results show that the properties of the nearly 30-year-old material exceed the NSF-54 required values and the more restrictive PGI-1103 values. For example, the tensile property data shows a sufficient percent elongation at break (greater than 360%) in both the MD and TD directions, which indicates that the material retained its flexibility. It can also be seen that the TRI/Environmental values of elongation at break are a little higher than the UIUC values but in agreement, and both exceed the NSF-54 and PGI-1103 values. Samples were also tested to determine the secant modulus of elasticity, a measure of geomembrane flexibility even after nearly 30 years in an aquaculture environment, which is calculated using the load required to achieve 100% axial

Table 1. Summary of Tests and Specifications.

Test Description	ASTM Specification (11)	NSF-54	PGI-1103
Break strength (kN/m)	D 882, Method A	8.1	8.4
Elongation at break (%)	D 882 (A)	325	360
Secant modulus at 100% strain (kN/m)	D 882 (A)	3.5	3.7
Tear resistance (N)	D 1004	26.7	27.0
Bonded seam shear strength (kN/m)	D 882	6.4	6.7
Hydrostatic resistance (kPa)	D 751 (A)	413	470
Thickness (mm)	D 5199, D 1593	0.48	0.49
Dimensional stability (% change)	D 1790 (100°C, 0.25 hr)	± 5	± 4
Water extraction (% change)	D 3080	−0.25	−0.15
Volatile loss (% loss)	D 1203	0.90	0.90
Low temperature brittleness (% passing)	D 1790	80	80

strain in the tensile test. A low secant modulus indicates a softer, more elastic/flexible material, while a high modulus indicates a stiffer material. The secant modulus is approximately two times higher than the specified value, which indicates that some hardening occurred over the 30 years of service. The hardening also may have contributed to the result that the tensile break strength values comfortably exceeded both specifications. In summary, the engineering properties of the nearly 30-year-old submerged material exceed both the NSF-54 and the PGI-1103 specifications even though the material was desiccated prior to testing.

The results of the water extraction and volatile loss tests also confirm sufficient plasticizer retention after nearly 30 years. One interesting result is the water extraction data. The UIUC data indicates a gain in water during the test, as did the TRI/Environmental data, albeit to a lesser degree. This may be attributed to desiccation of the material prior to testing and the material gaining water during the test to return near the field condition. This behavior reinforces the recommendation that exhumed specimens should be tested at *in-situ* moisture conditions and not after desiccation.

The factory geomembrane seams were created using a solvent, and the performance of the seams over approximately 30 years was of particular interest. It can be seen from *Table 2* that the bonded shear strength exceeds the recommended NSF-54 and PGI-1103 values. Peel tests of the seams were not conducted because the factory solvent seams did not have a “flap” to permit peel testing. TRI/Environmental did not test a seam because the material that was shipped did not contain a seam. In summary, factory solvent seams appear to be extremely durable, which is important because PVC geomembranes in projects of this size can be fabricated entirely in the factory, folded, and shipped to the site for installation. This allows every seam to be made under controlled factory conditions. On large projects, some field seaming may be required, and research is being conducted to investigate the behavior of field PVC seams (8, 9), but factory seams appear to be satisfactory.

Plasticizer retention is more difficult in an aquatic environment than a non-aquatic environment because as the water or liquid continuously circulates, it provides a continuous opportunity for plasticizer to migrate into the liquid (10). In addition, the thinner the PVC geomembrane, the larger the impact of surficial plasticizer loss on the engineering properties will be. For example, the percentage change in engineering properties can be greater for a 0.51-mm versus a 0.76-mm-thick PVC geomembrane. Therefore, the test results on a 0.51-mm-thick PVC geomembrane after nearly 30 years in an aquatic environment still exceeding the NSF-54 and PGI-1103 recommended values is significant in confirming plasticizer retention with time. This also indicates that the formulation was proper and the plasticizer was sufficiently retained even in a harsh aquatic environment.

Material from above the waterline was also desiccated prior to testing in accordance with ASTM Standard Test Methods, and the results are shown in *Table 3*. It is expected that plasticizer retention above the waterline will be higher than that below the waterline, as water is not continuously present to remove some of the plasticizer. Evidence of greater plasticizer retention can be seen in comparing the tensile properties in *Tables 2* and *3*. For example, the break strength is lower for the material above the waterline, indicating a slightly softer material than below the waterline. This additional plasticizer retention above the waterline is also reflected in the larger value of percent elongation at break (369% versus 362%) and a lower value of secant modulus (8.4 kN/m versus 9.8 kN/m) in the machine direction than the below-waterline material. This suggests that the material is more flexible above the waterline probably because of greater plasticizer retention. As in *Table 2*, the water extraction data shows a

Table 2. Desiccated, Machine Direction/Transverse Direction Properties for Desiccated Material Exhumed From Below the Water Level.

Test	UIUC	TRI
Break strength (kN/m)	12.6/10.3	10.9/10.5
Elongation at break (%)	362/361	368/447
Secant modulus at 100% strain (kN/m)	9.8/8.9	*
Tear resistance (N)	59.2/53.8	37.4/36.4
Bonded seam shear strength (kN/m)	9.1	*
Hydrostatic resistance (kPa)	1029	710
Thickness (mm)	0.48	0.52
Dimensional stability (% change)	−4.0/−1.4	−2.0/0.9
Water extraction (% change)	0.09	0.04
Volatile loss (% loss)	0.01	0.26
Low temperature brittleness (% passing)	83	100

*Not tested

Table 3. Machine Direction/Transverse Direction Properties for Desiccated Material Exhumed From Above the Water Level.

Test	UIUC
Break strength (kN/m)	10.5/10.0
Elongation at break (%)	369/361
Secant modulus at 100% strain (kN/m)	8.4/8.2
Tear resistance (N)	50.2/47.1
Bonded seam shear strength (kN/m)	8.6
Hydrostatic resistance (kPa)	1034
Thickness (mm)	0.48
Dimensional stability (% change)	−4.0/−4.0
Water extraction (% change)	0.10
Volatile loss (% loss)	0.10
Low temperature brittleness (% passing)	83

gain in water during the test, which may be caused by desiccation prior to testing. In summary, the data in *Table 3* shows there is greater plasticizer retention in a non-aquatic environment, which results in a greater retention of flexibility even after nearly 30 years. This suggests that a PVC geomembrane in a non-aquatic environment, such as a landfill cover system, should experience excellent plasticizer retention and at a minimum better retention and performance than the below-water-level material, which exhibited good performance for nearly 30 years.

In addition to testing the desiccated material according to the applicable ASTM standards, specimens were maintained and tested at their *in-situ* water content. These results are summarized in *Tables 4* and *5* for samples obtained below and above the water level, respectively. The secant modulus of the *in-situ* moisture content specimens is smaller than that of the desiccated material. This indicates that the PVC is more flexible at field moisture conditions than after it is desiccated. The elongation at break is also correspondingly larger for the non-desiccated material because it is more flexible than the desiccated material.

The *in-situ* results for the volatile loss and water extraction tests may be inaccurate because the ASTM procedure involves weighing samples before and after the tests and the specification was intended to be used for desiccated material. Therefore, the specification values are based on desiccated weights of the material and may not be meaningful for material that was tested at the field water content. It is proposed herein that testing exhumed geomembrane at the *in-situ* conditions provides a better representation of the field behavior than desiccating the samples. Therefore, ASTM D3080 and D1203 should be modified to allow testing of exhumed geomembranes at field conditions.

Table 4. Machine Direction/Transverse Direction Properties for Non-Desiccated Material Exhumed From Below the Water Level.

Test	UIUC
Break strength (kN/m)	12.4/11.6
Elongation at break (%)	384/386
Secant modulus at 100% strain (kN/m)	9.4/9.1
Tear resistance (N)	57.8/50.3
Bonded seam shear strength (kN/m)	9.3
Hydrostatic resistance (kPa)	941
Thickness (mm)	.48
Dimensional stability (% change)	−2.5/−0.7
Water extraction (% change)	0.40
Volatile loss (% loss)	−1.13
Low temperature brittleness (% passing)	83

Table 5. Machine Direction/Transverse Direction Properties for Non-Desiccated Material Exhumed From Above the Water Level.

Test	UIUC
Break strength (kN/m)	11.8/10.3
Elongation at break (%)	394/412
Secant modulus at 100% strain (kN/m)	8.4/7.9
Tear resistance (N)	49.8/46.7
Bonded seam shear strength (kN/m)	8.6
Hydrostatic resistance (kPa)	903
Thickness (mm)	0.48
Dimensional stability (% change)	−4.0/−3.9
Water extraction (% change)	0.41
Volatile loss (% loss)	−0.11
Low temperature brittleness (% passing)	83

CONCLUSION

After nearly thirty years of service in an aquatic environment, a 0.51-mm-thick PVC geomembrane retained its flexibility and strength, enabling it to perform as a successful water barrier. This indicates that plasticizer retention in an aquatic environment is not a problem even with 0.51-mm-thick material. These results are significant because they not only support the use of PVC geomembranes in aquatic applications, but also support their use in non-aquatic applications, because a non-aquatic environment is less problematic in terms of plasticizer retention than an aquatic environment. This is reinforced by comparison of the test results for material from above and below the waterline, which shows plasticizer retention is greater for the above-waterline material in *Tables 4* and *5*. This case history also shows that PVC geomembrane material and its seams are not compromised or deteriorated by root penetration or microorganisms after nearly 30 years, even though the material is only 0.51 mm thick.

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